Multilayer and thin film coatings for EUVL and beyond

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Disclaimer

~~Study of MLM structure layer by layer during growth or sputtering using low energy ion scattering (LEIS).~~

Study of MLM structure after deposition using X-ray reflectivity (XRR) and X-ray standing waves (XSW).

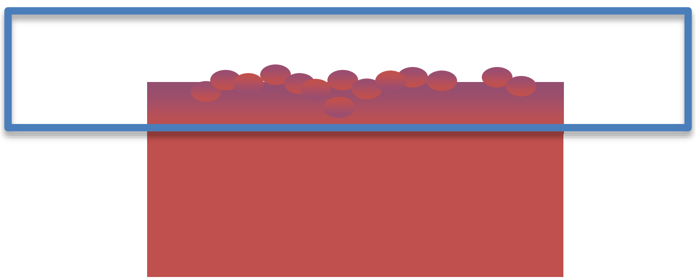
No reflectivity curves!

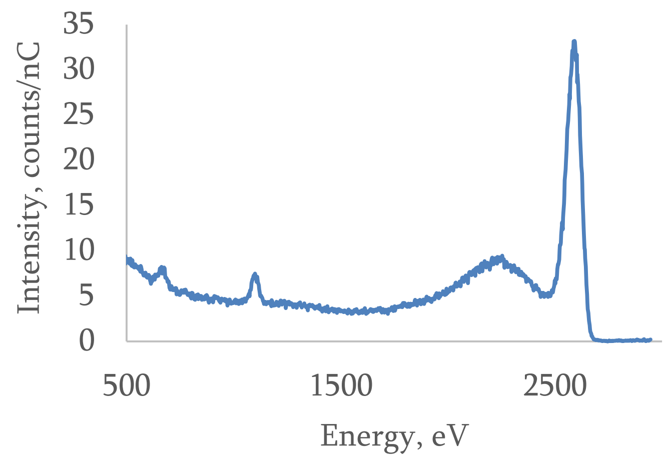
Two highlights: tools to understand the physics of ML growth.

Ultra-thin film growth

What is the chemical composition profile of the interfaces?

What is the minimal thickness of the layer when closed?





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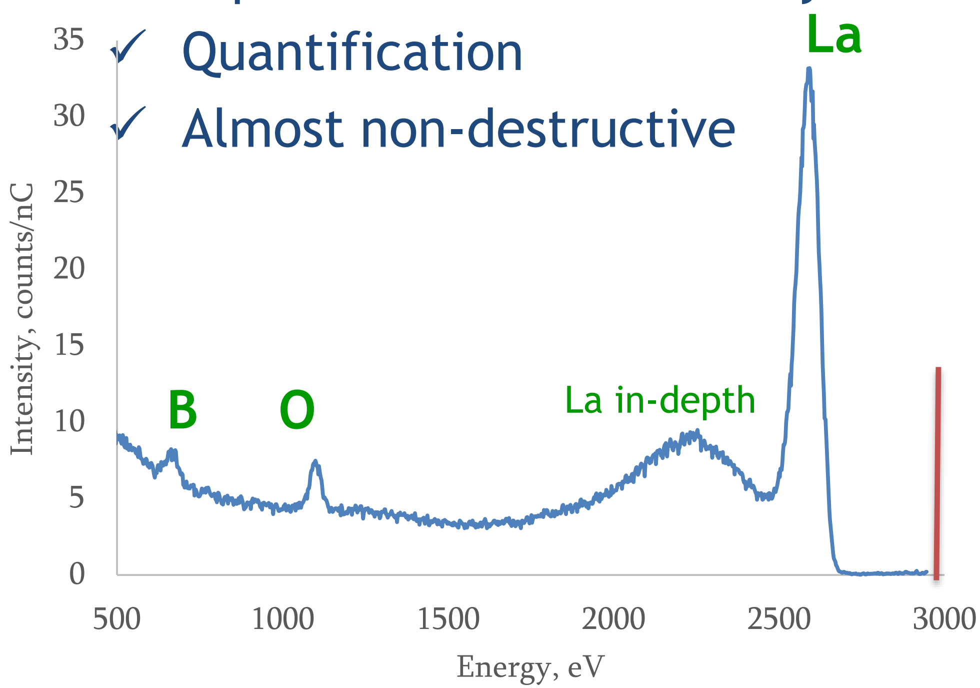
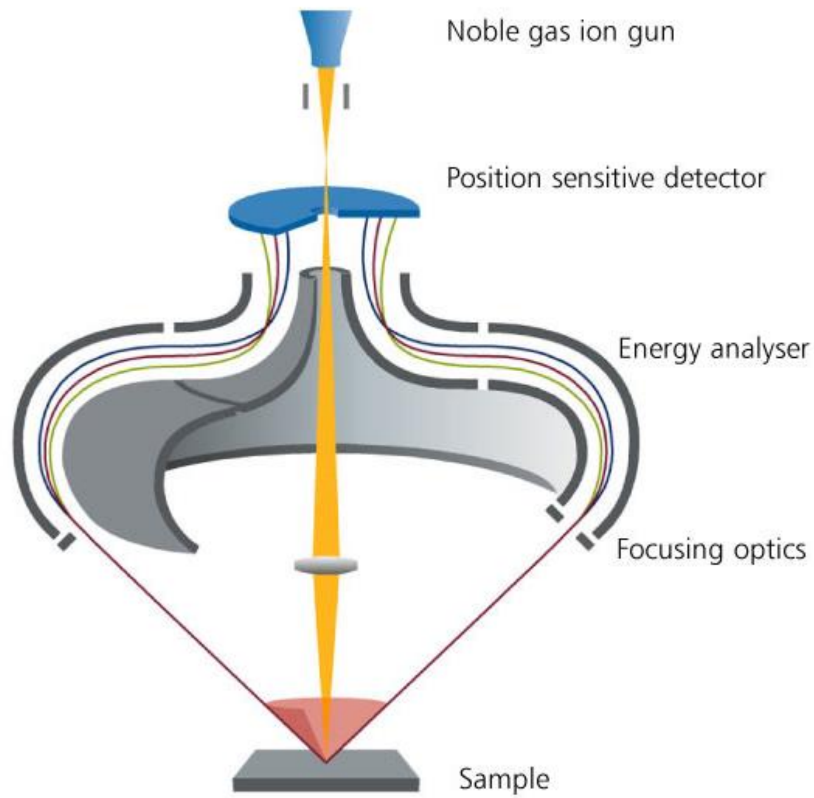
Low Energy Ion Scattering (LEIS)

extreme sensitivity to surface

- ✓ Noble gas ions with low energy
  - 0.1 - 10 keV
  - He^+, Ne^+, Ar^+
- ✓ High neutralization rate – topmost surface sensitivity
- ✓ Quantification
- ✓ Almost non-destructive





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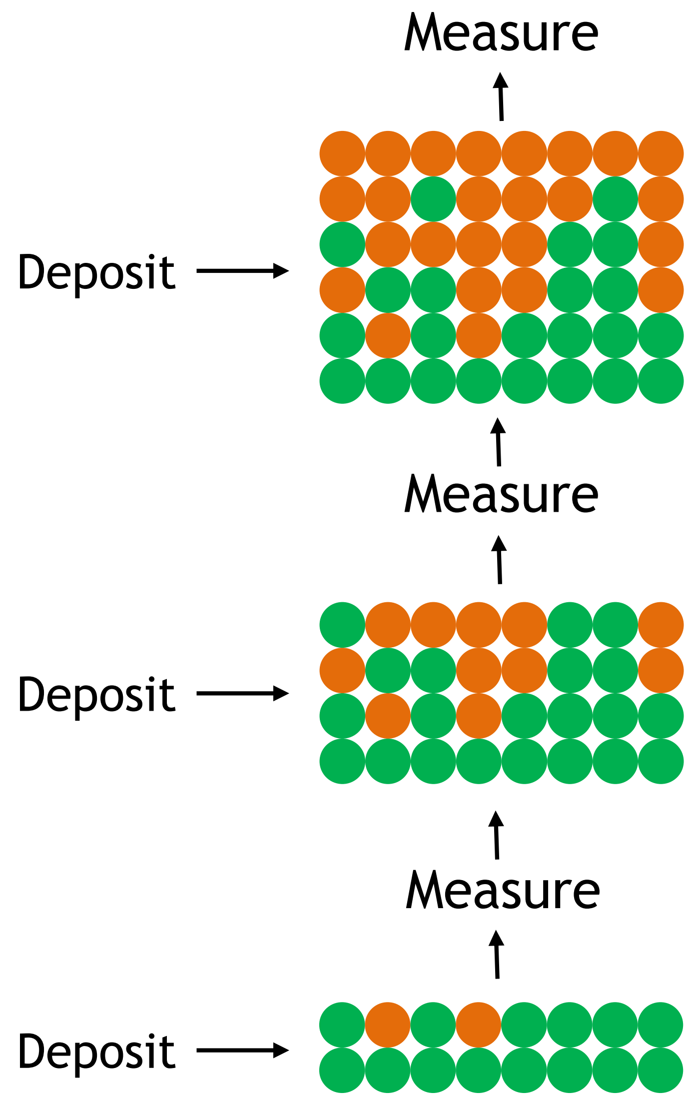
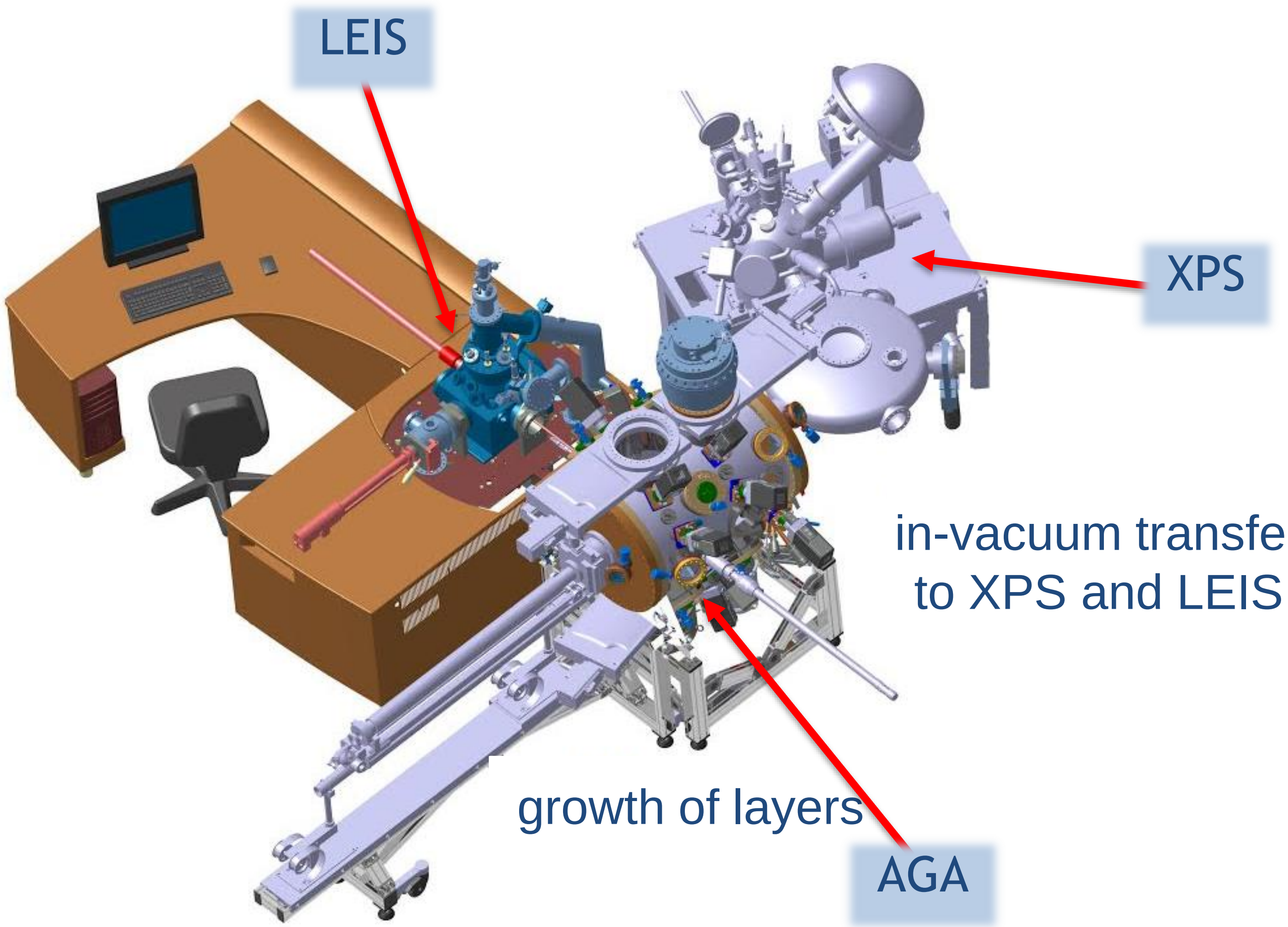
LEIS depth profiles

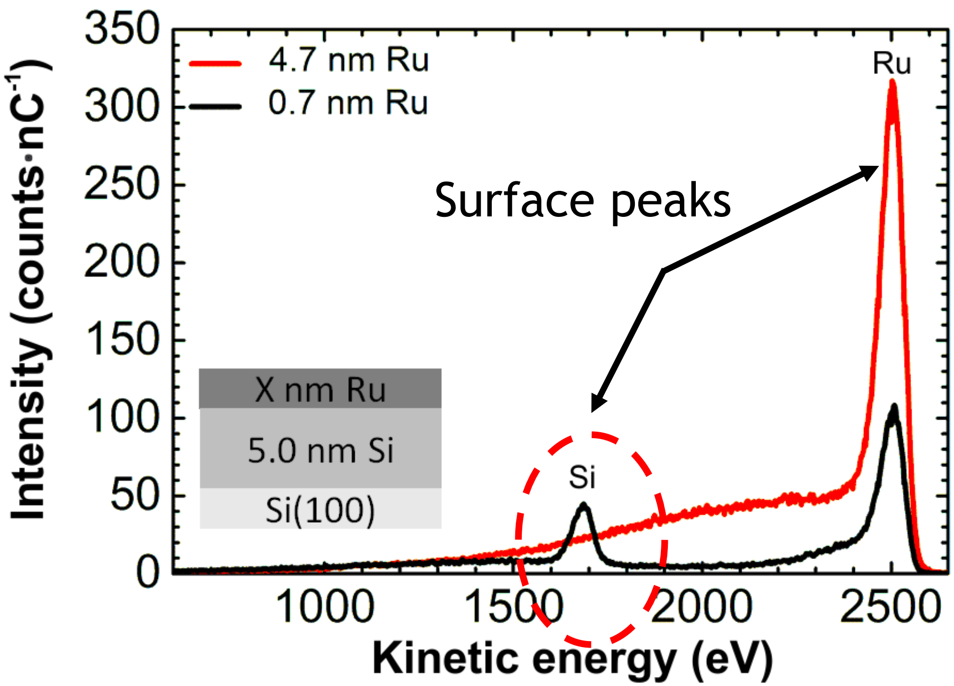
- ✓ Sputter depth profile
  - remove layer by layer and measure
  - problems:
    - sputter-induced intermixing
    - preferential sputtering
- ✓ Deposition depth profile
  - deposit layer by layer and measure
  - problems:
    - surface segregation effects



Single interface LEIS-XPS cluster



LEIS Measurement of layer closure



LEIS Measurement:

Primary ion: He

Primary energy: 3 keV

Surface coverage calculations:

$$C_i^{surf} = \left[\sum_{j=1}^{j_{max}} \frac{S_j S_i^{ref} N_j^{ref}}{S_i S_j^{ref} N_i^{ref}} \right]^{-1}$$

Closed Ru layer determination: Si surface peak vanishes

Ru growth on Si surface

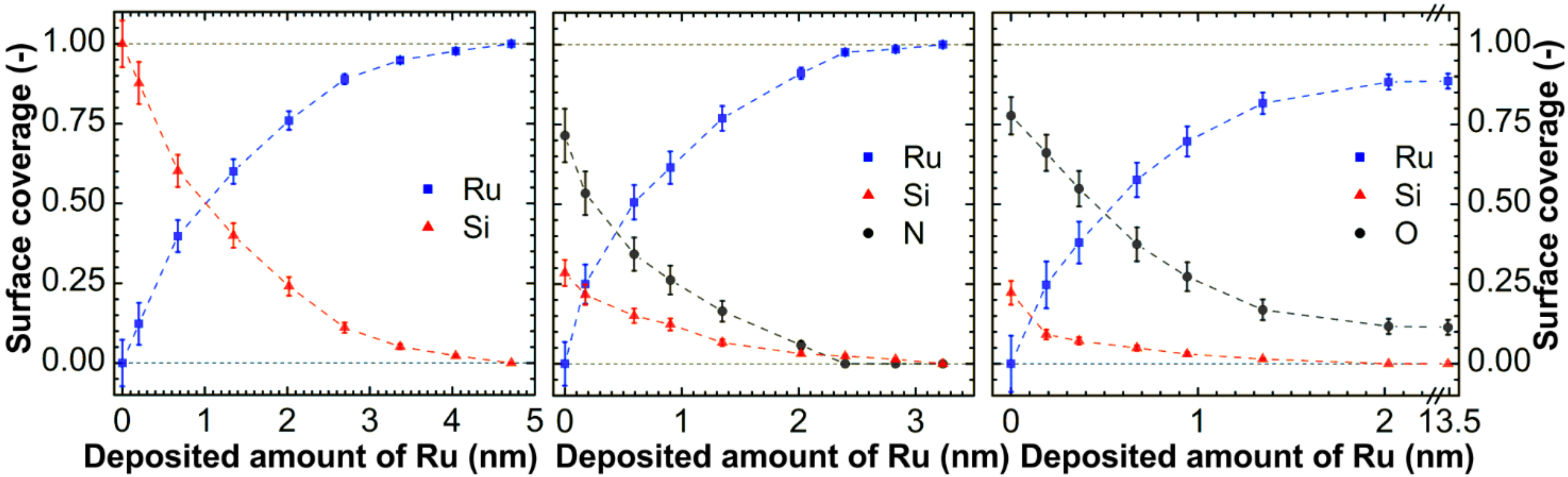
Studied samples:

Ru on Si (Unpassivated)	Ru on SiN (N passivation)	Ru on SiO_2 (O passivation)
X nm Ru	X nm Ru	X nm Ru
5.0 nm Si	1.5 nm SiN	1.5 nm SiO_2
	4.0 nm Si	4.0 nm Si
Si(100)	Si(100)	Si(100)

X= 0 to 5 nm

In-vacuo monitoring Ru growth

Ru on Si | *Ru on SiN* | *Ru on SiO_2*



Huge Ru-Si intermixing
->$RuSi_x$ formation

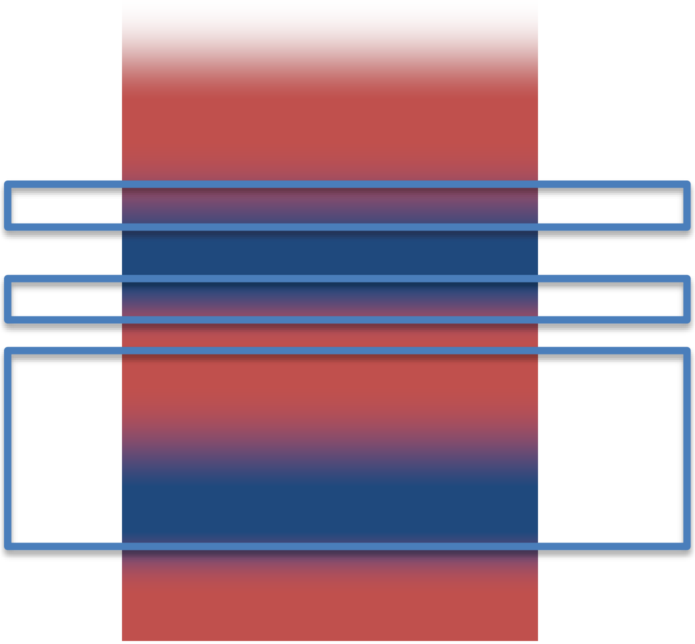
Less Ru-Si
interface on SiN

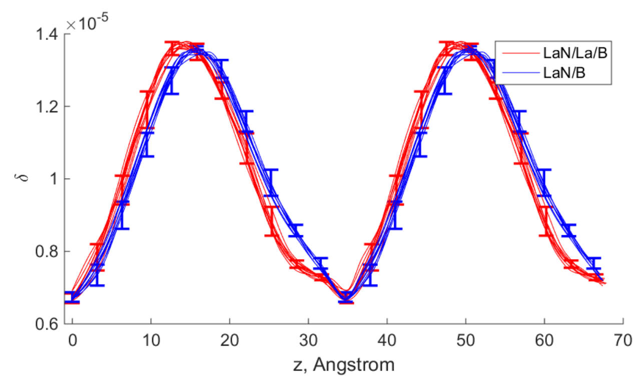
Even less Ru-Si
interface on SiO_2
Surface O after closing
the layer

R. Coloma-Ribera et.al., J. of Appl. Phys. **120**, 065303 (2016).

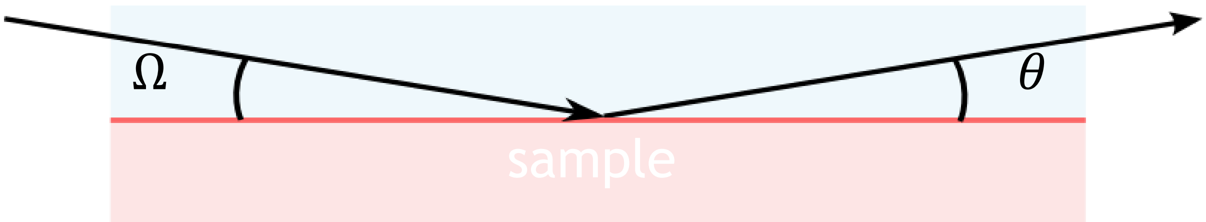
MLM interfaces and optical contrast

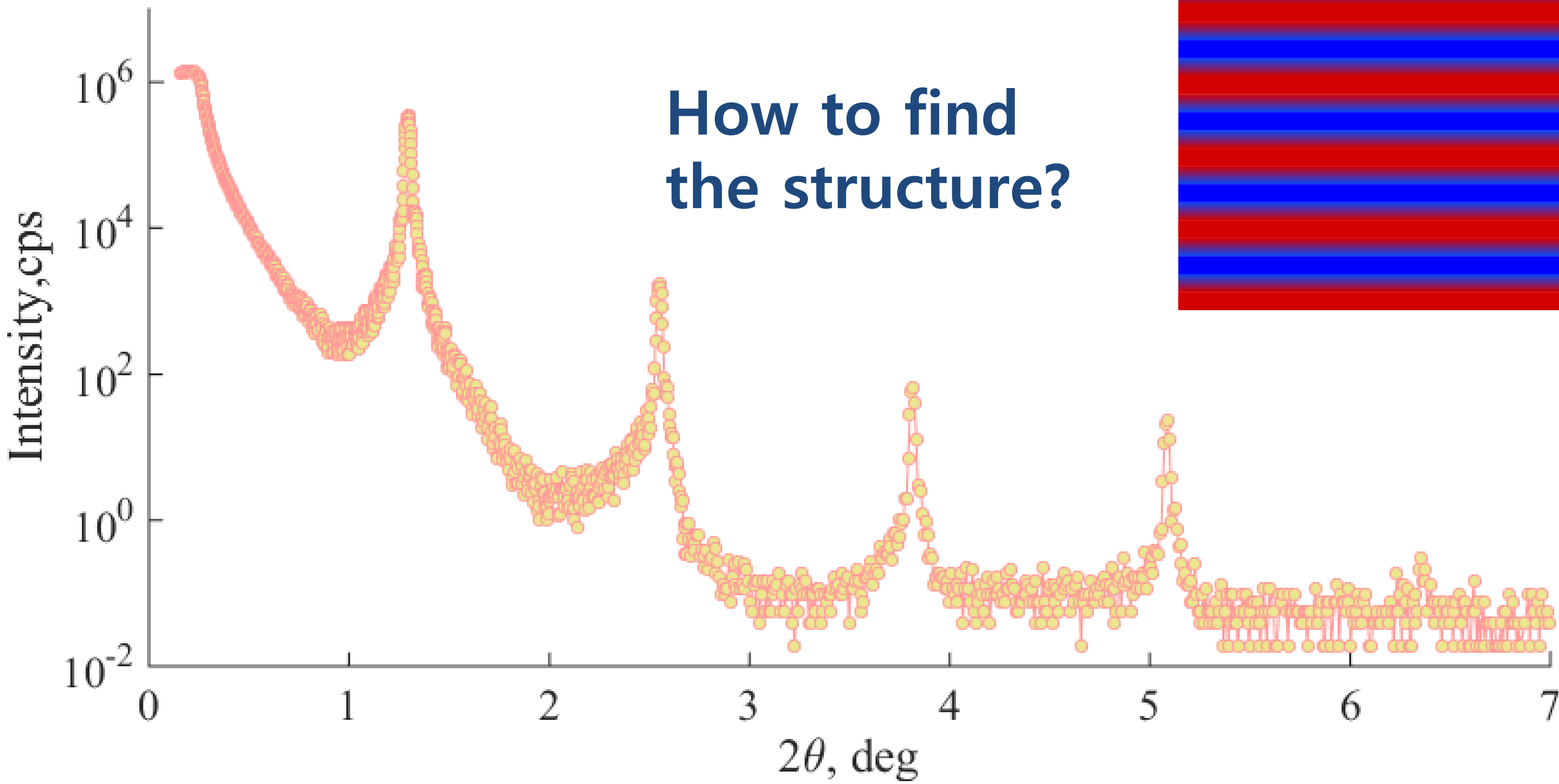
MLM period structure?



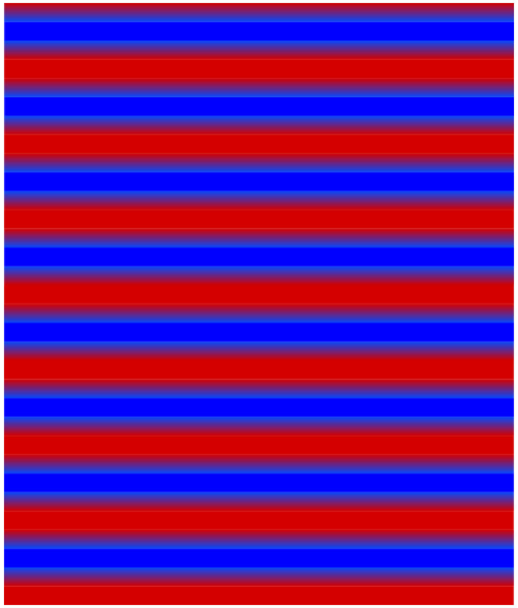


Grazing Incidence X-Ray Reflectivity





How to find the structure?



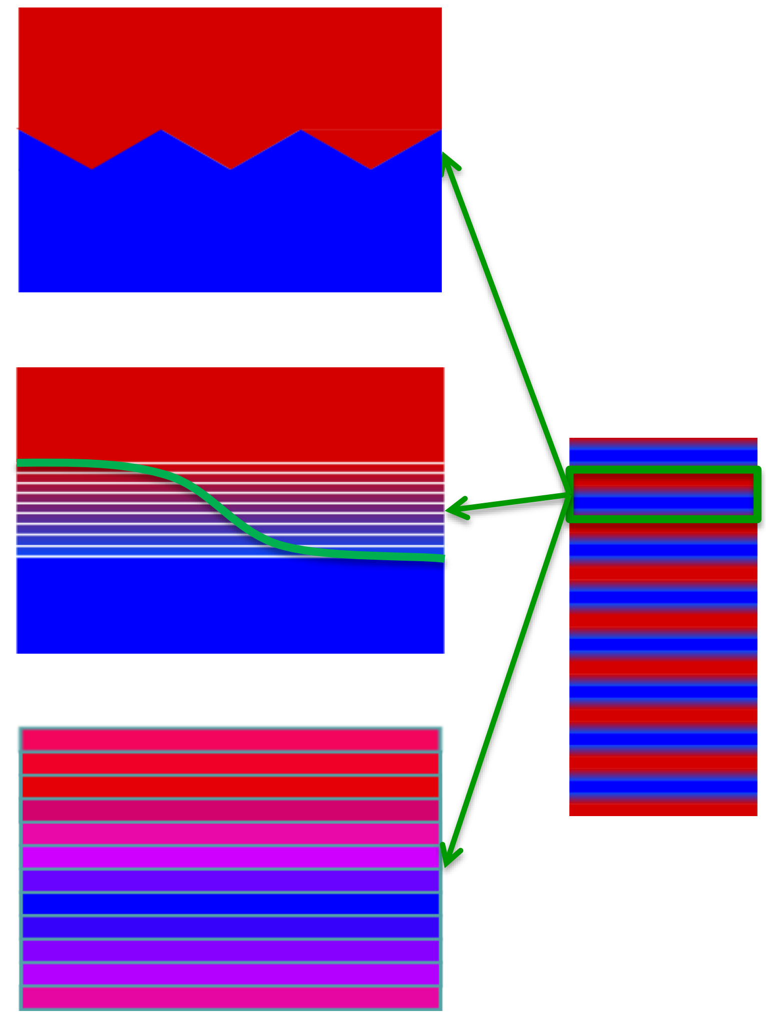
Process of reconstruction

- ✓ General idea
  - inverse problem solution – fitting of model to GIXRR

1 Representation of structure
  - Sharp layers with Debye-Waller or Nevot-Croce factors
  - Transition layers
  - Free-form

2 Calculation of GIXRR from model
  - kinematic theory
  - dynamic theory

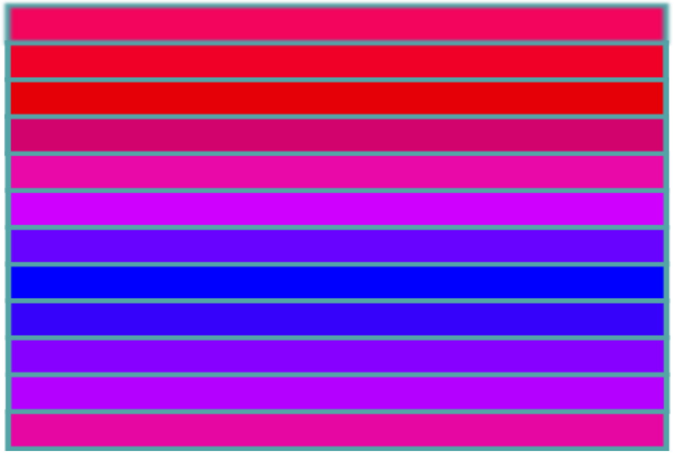
3 Fitting the model to the measurement



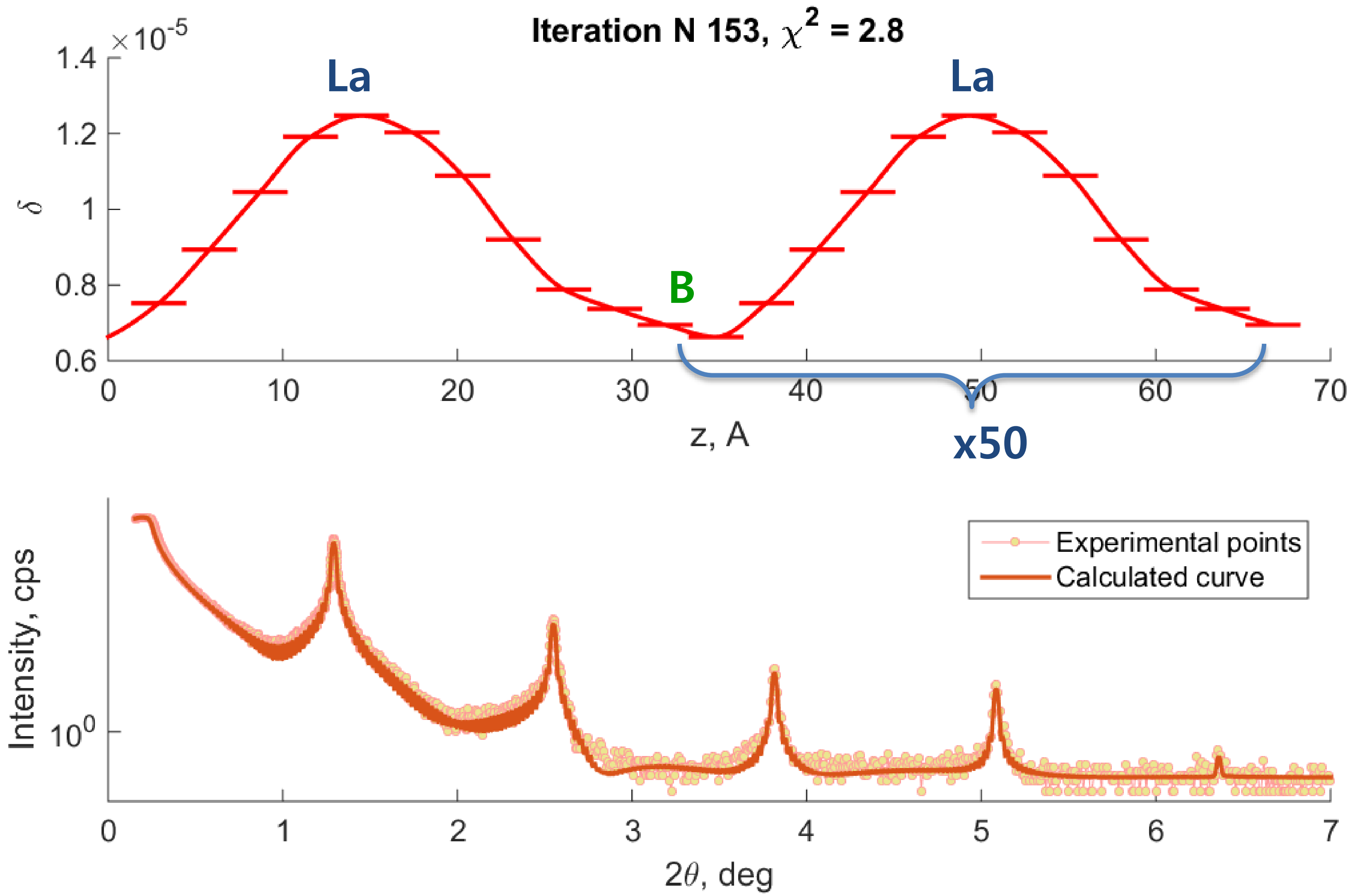
Free-form approach

- ✓ Full period is divided into separate sublayers with fixed thickness
- ✓ Refractive index of each sublayer is fitted separately
- ✓ Pre-knowledge about interfaces is not required
- ✓ First time application to periodic structures

- ✓ Input: 2 materials
- ✓ Output: n for every sublayer ($n = 1 - \delta + i\beta$)



Evolution of fit



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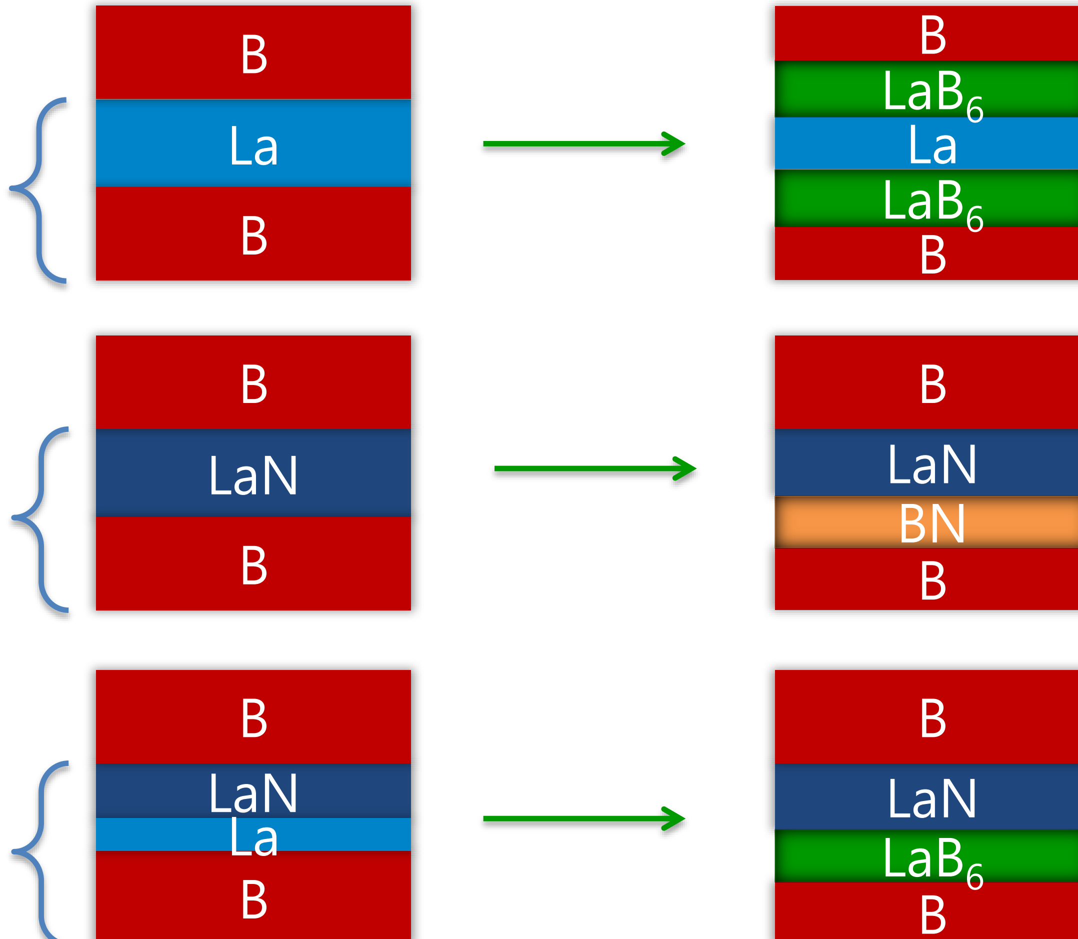
Interface compounds

~3.5 nm



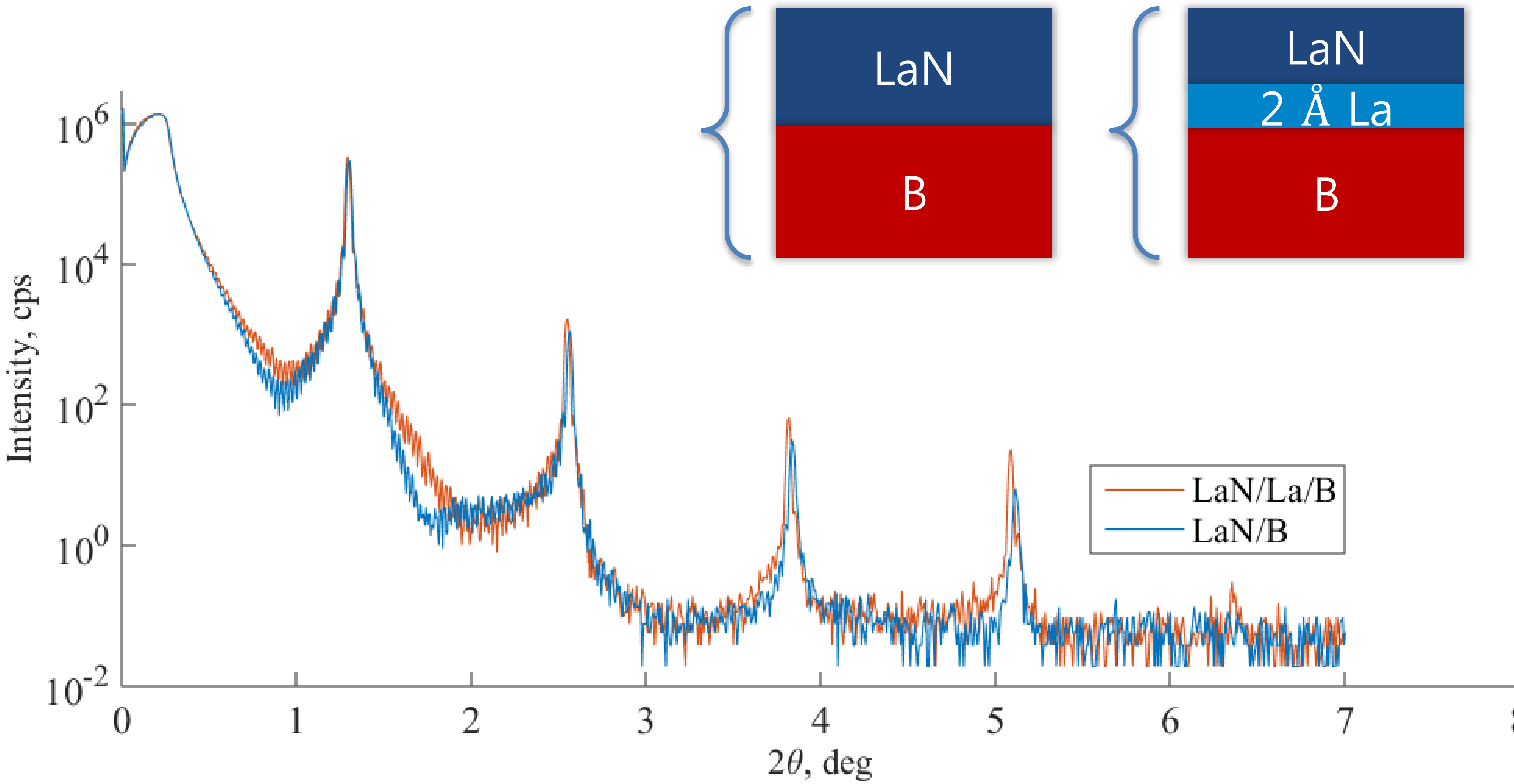
Reflectance for full stack at λ =6.7 nm (BEUV):

- 58.3% for LaN/B
- 64.1% for LaN/La/B

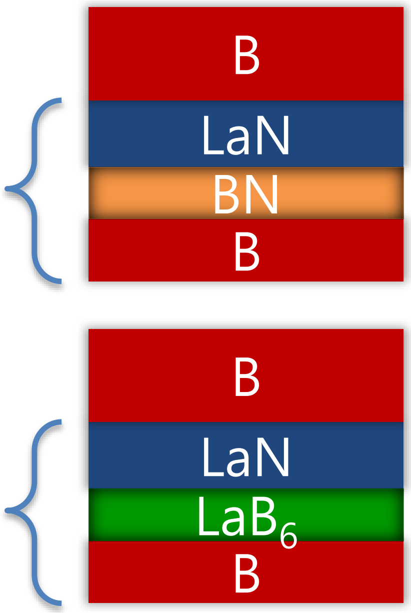
D. Kuznetsov et al. "High-reflectance La/B-based multilayer mirror for 6.x nm wavelength", Optics Letters 40 16 (2015)

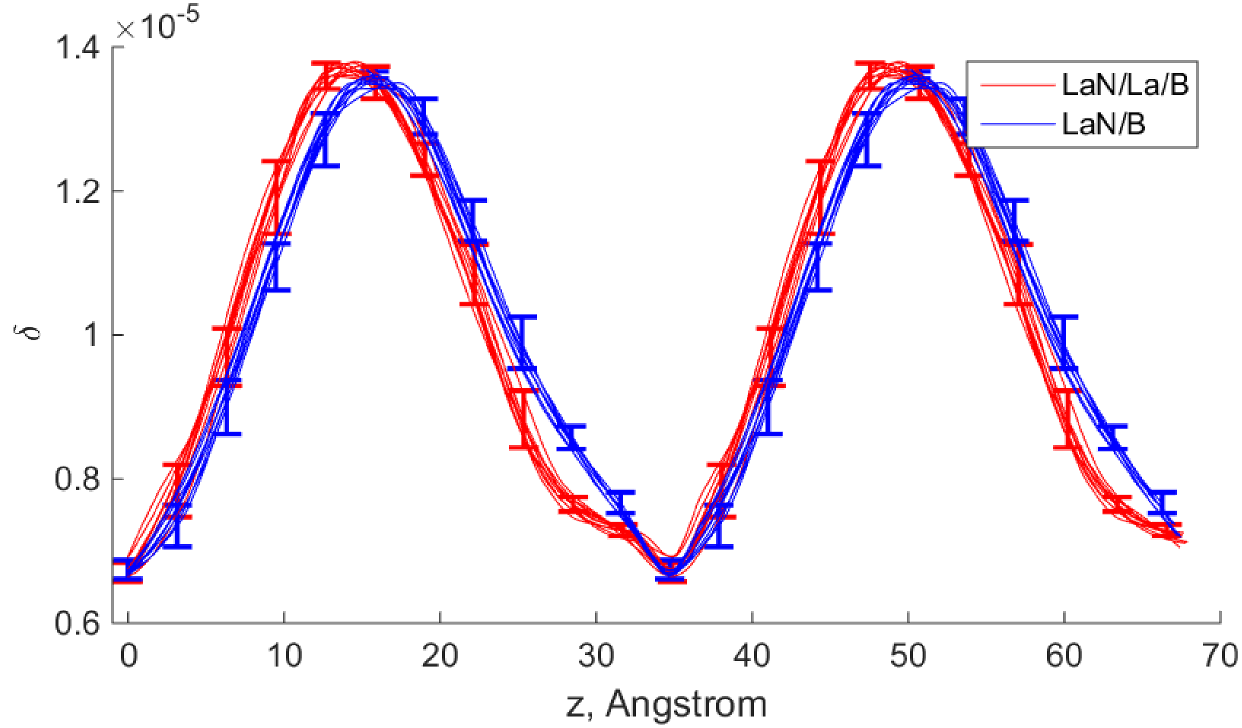
Experimental data

✓ Two 3.5 nm LaN/B multilayer (50 periods) samples:



Fit of experimental data





- ✓ Difference in δ-profiles – on top of B layer
- ✓ Can be explained by:
  - sharper La-on-B interface due to absence of BN in LaN/La/B
  - thin La boride interlayer formation on top of B layer in LaN/La/B

A. Zameshin et. al. J. Appl. Cryst. (2016). **49**, 1300–1307

Summary

- *Multilayer optics development is continuously further enabled by advanced analysis*
- In vacuo-LEIS: currently most sensitive surface analysis technique
  - Demonstrated for monitoring thin film growth and determination of layer closure e.g. for Ru on Si, SiN and SiO_2, and Si on Ru systems;
  - Ru growth is driven by Ru-Si formation, which is reduced by Si passivation;
  - Si segregation on Ru surface can explain huge Ru-Si intermixing for Ru on Si system;
- Free-form x-ray reflectivity analysis allows full reconstruction of optical constant profiles of periodic multilayers;
  - Very good fits for model system and experimental data;
  - Reconstructed profiles of LaN/B-based multilayers reveals differences in compound formation on LaN-on-B interface;

Thank you